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Fuzzy-PID Controller Design of 4 DOF Industrial Arm Robot Manipulator

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ABSTRACT

The arm robot manipulator is the most applied robot to substitute human labor in industries. Due to the importance of arm robot manipulator in manufacturing lines, the robustness and effective design are essential in building an arm robot. This paper presents the controller, mechanical, and motion designs of an arm robot manipulator. The fuzzy logic controller is employed to ensure the effectiveness in detecting the target object. PID controller is designed to ensure the smoothness and stability of robot motion. The best setup for Kp is 20 and Kd is 2.9 reaching the result to least transient time and stable steady state. The simulation of how the robot move inside its workspace was conducted using RSTX toolbox in SciLab. The motion is generated by deriving Denavit-Hartenberg parameters of the mechanical design. The simulation result gave 120^{O} for θ_1, 90^{O} for θ_2, θ_3, and θ_4 as the most effective angles for the robot to move in its workspace. The results show the effective design of Fuzzy-PID controller and mechanical design of a pick and places arm robot manipulator.

Keywords: Arm robot manipulator, fuzzy logic controller, pick and place, PID controller**.**

1. INTRODUCTION

A robot is a machine that can be programmed to carry out a task to substitute human. Robots are divided into three, namely mobile robots, manipulator robots, and hybrid robots [1]. The origin of robot application in human life is an industrial robot.Therefore the term robot is closely related to automation. The most commonly used industrial robot is arm robot manipulator that can come in term of a very simple robot and easily applied to substitute human working in manufacturing lines. The arm robot can be customized to imitate the human arm and finger (end-effector) for completing tasks such as pick and place robot, and welding [2]-[7].

The role of robot manipulators plays the most crucial part in the last few years in the industrial automation such as in automotive, electronics, computer, even food, and beverage industry. Those applications objectives are to substitute human working in a dangerous, dull, and repetitive environment. Therefore, robot motion has to be controlled and programmed to get motion as smooth as the human's [8].

The most applied actuator in building an arm robot manipulator is servo motor due to its robustness in controlling its motion, therefore, in turn, making it easier to control robot motion. In order to function correctly in many applications, the arm robot should include the application of sensors such as a camera for the "eye" to see the object to be manipulated or proximity sensor to detect the distance of robot to the manipulated object. The inputs from sensors are the input base of the robot motion [7]-[10].

Design robot requires a controller to optimize the robot's function to ensure the stability and robustness during robot movement. Proportional-integral-differential (PID) controller is the primary controller used in most robots applications, and however, in most cases, the PID controller only is not enough for controlling the robot [11][12]. An artificial intelligence (AI) needs to be added, one of the AI is the fuzzy logic controller (FLC) [13][14]. Robotics is entitled with complex mathematical modeling. By applying FLC, the complexity can be avoided and control the robot by considering the inputs from sensors without including sensors' model in dynamic modeling [15]-[19].

This paper discusses the design of 4 Degree of Freedom (DOF) arm robot manipulator in term of the controller, mechanics, and motion analysis. The controller design combines the conventional PID controller with FLC to create robust and stable robot motion. The most straightforward control system on robots is the PID system functioning as a regulator of servo motor movement installed on the links of the arm robot; therefore, error in moving the robot can be reduced. Robot motion inside its workspace is simulated by SciLab's RSTX toolbox [20] by deriving Denavit-Hartenberg parameters [21] from mechanical design.

2. THE PROPOSED METHOD

Figure 1 shows the proposed method discussed in this paper. FLC is the linguistic controller to move the robot based on the camera detection upon the assigned color written on rules-based shown in Table 1. The efficiency and smoothness of robot motion are controlled by the conventional PID controller. This paper shows FLC and PID controller design for a pick and place robot.

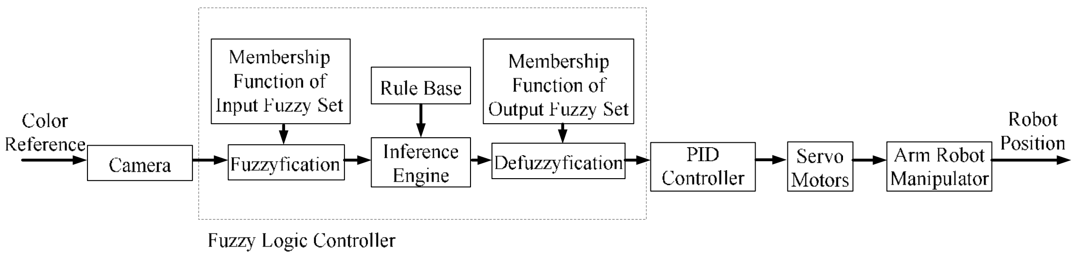

FIGURE 1. The schematic diagram of the proposed method

2.1 FUZZY LOGIC CONTROLLER DESIGN

Fuzzy logic controller (FLC) is derived from mathematical logic that analyzes the analog inputs whose values are between 0 and 1 as the contrast with digital input whose values are 0 or 1. Lotfi A Zadeh first introduced fuzzy logic in his 1965 and 1973 paper, and he elaborated his fuzzy logic within the concept of linguistic variables defined as a fuzzy set. FLC first implemented in an inverted pendulum by Takeshi Yamakawa in 1987. Since then due to its simplicity, FLC is widely applied in the control system.

A fuzzy set is the input variables in the control system that mapped a set of the membership function. These inputs are derived from the output of a sensor attached

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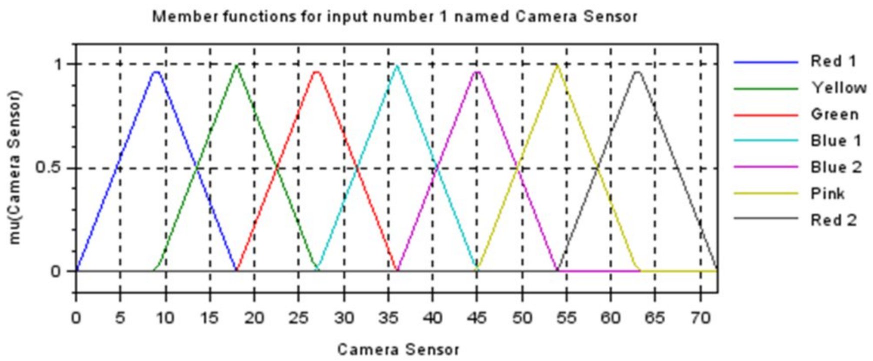
to the system. FLC can be implemented without considering the complex mathematical model of sensors. The fuzzy set in FLC mapping input variables into membership function and truth values, then the controller makes the decision based on the membership function. The FLC applied in this study considered the rules-based on the sensors inputs attached to the arm-robot.

TABLE 1.
Rules based of 4 DOF robot considered in this study

Camera Sensor	Proximity sensor	Motor 1	Motor 2	Motor 3	Motor 4
Red	Near	Stop	Stop	Stop	Stop
Red	Medium	Stop	Stop	Stop	Stop
Red	Far	Stop	Stop	Stop	Stop
Yellow	Near	Stop	Stop	Stop	Stop
Yellow	Medium	Stop	Stop	Stop	Stop
Yellow	Far	Stop	Stop	Stop	Stop
Green	Near	Slow	Slow	Slow	Slow
Green	Medium	Medium	Medium	Medium	Medium
Green	Far	Fast	Fast	Fast	Fast
Sky blue	Near	Stop	Stop	Stop	Stop
Sky blue	Medium	Stop	Stop	Stop	Stop
Sky blue	Far	Stop	Stop	Stop	Stop
Navy	Near	Stop	Stop	Stop	Stop
Navy	Medium	Stop	Stop	Stop	Stop
Navy	Far	Stop	Stop	Stop	Stop
Pink	Near	Stop	Stop	Stop	Stop
Pink	Medium	Stop	Stop	Stop	Stop
Pink	Far	Stop	Stop	Stop	Stop
Red	Near	Stop	Stop	Stop	Stop
Red	Medium	Stop	Stop	Stop	Stop
Red	Far	Stop	Stop	Stop	Stop



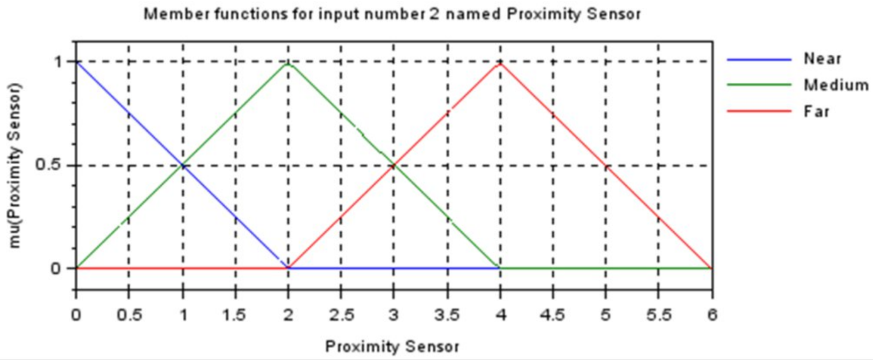


FIGURE 2. The membership function for the inputs simulated in SciLab

A membership function maps the relationship between the output of FLC and the inputs, and in this paper, the membership function used is the triangular curve. Figure 2 shows the membership function mapping the input from a camera, distance sensor, and 4 output of motor servo.

The camera acting as sensor gives 7 fuzzy set of colors, namely Red (0-18), Yellow (9-27), Green (18-36), Light Blue (27-45), Dark Blue (36-54), Pink (45-63), Red (54-72). The fuzzy set of distance sensor is given by Near (1-2), Medium (2-4), and Far (4-6). Figure 3 shows the fuzzy set of motor servo (1, 2, 3, 4) output with the variable of a stop, slow, medium, and fast.

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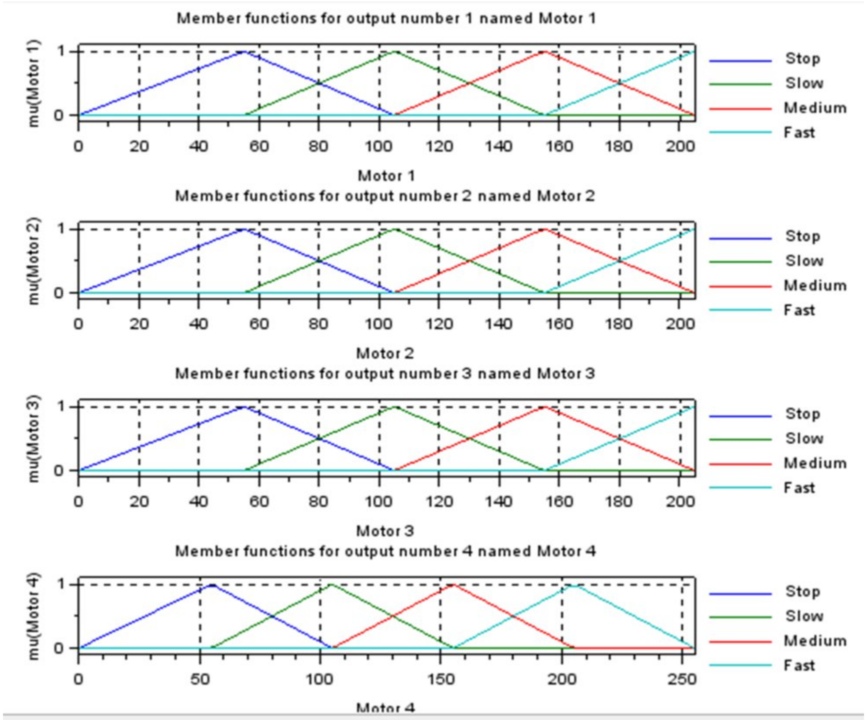


FIGURE 3. The membership function for the output simulated in SciLab

These outputs are connected to the robot motion. The fuzzy set of output consists in the range of stop (0-105), slow (55-155), medium (105-205), and fast (155-125).

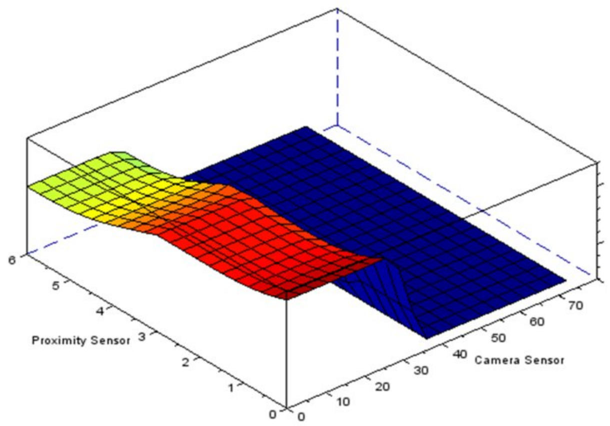
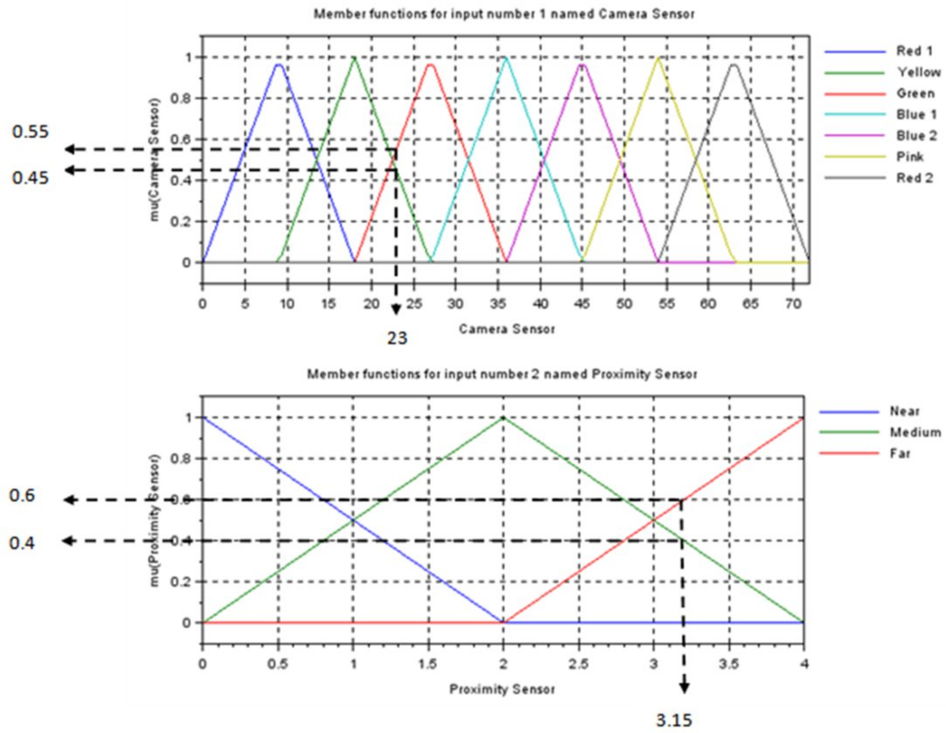


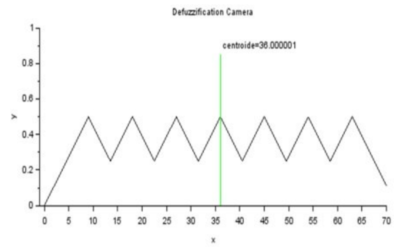
FIGURE 4. 3D output simulated in SciLab

FLC has 3 steps; fuzzification, a process in an inference engine, and defuzzification. Fuzzification is the process to change the value of input into the crisp input in term of linguistic; in this study red, yellow, green and blue based on the particular membership set. The output of fuzzification goes to an inference engine that uses the reasoning achieved from the fuzzy rules that have been determined to produce fuzzy output.

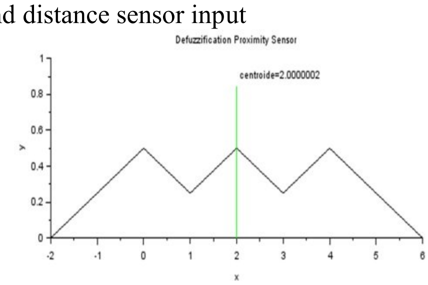
Figure 5a shows a fuzzification where the input from the camera is shown with green lines, for example when the camera gives the value of 23, the inference engine interpret it to be 0.55. The defuzzification is where the fuzzy rules change the fuzzy output to be crisp value based on the assigned membership function.



(a) The fuzzification of camera and distance sensor input



(b) The defuzzification of camera input



(c) The defuzzification of distance input

FIGURE 5. The fuzzification and defuzzification of sensors inputs

The method used for defuzzification is applied to the system by deriving the weighted average

$$y = \sum \frac{\mu(y)y}{\mu(y)} \tag{1}$$

where y is the crisp value and $\mu\ (y)$ is the degree of membership of crisp value.

The FLC is designed to detect a color out of 6 colors within difference range of colors. The assigned color in this study is green. The rules in Table 1 shown the complete rules or the possibility to choose "green." When the green object is detected and considered close, then the servos will active to move the manipulated object. As shown in table 1, the possible distances between the robot and the manipulated object are near, medium, and far, and the servo motors will rotate

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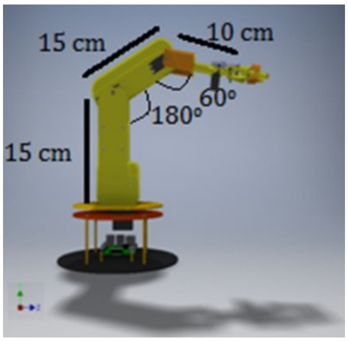
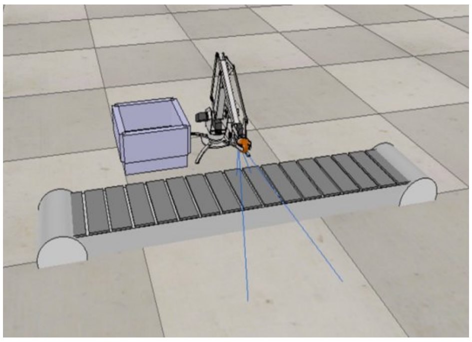
accordingly. The first detection would be from the camera, and the robot will move only when the green object is detected, other than that the robot remains in an idle position.

2.2 MECHANICAL DESIGN

Figure 6 shows the design of 4 DOF arm robot manipulator assigned to pick and place green object. Robot base height is 10 cm to ensure robot flexibility in picking and placing the manipulated object. Each link of 4 DOF is moved by JX-6221MG servo motor. Figure 6 shows the designed 4 DOF arm robot manipulator applied in this study. The robot is assigned to pick and place green fruit or object in the size of a tomato.



(a) Robot size



(b) Robot workspace

FIGURE 6. The mechanical design of 4 DOF arm robot

2.3 ELECTRONICS DESIGN

Figure 7 shows the electric design of the 4 D0F arm robot manipulator considered in this study. The design consists of a camera and raspberry PI for image processing, and microcontroller set included in Arduino, distance sensor, Lippo battery as the power supply, and 4 JX-6221MG servo motors. The main controller for the system is ATmega 2560 microcontroller with 54 I/O digital pins functioning as the processor from input to output. Image captured by the camera is processed in raspberry PI 3, and the output of the Raspberry PI is the input to the microcontroller and become the reference input to move the robot. To detect the position of the manipulated object whether it is far, medium and near, an ultrasonic HC-SR04 is employed. The symbols are shown in figure 7 is A is the power supply, B is a camera, C is the output block consists of 4 servo motors, D is raspberry PI, E is the Arduino as the main controller of the system, and F is the distance sensor to detect the distance between the robot and the manipulated object.

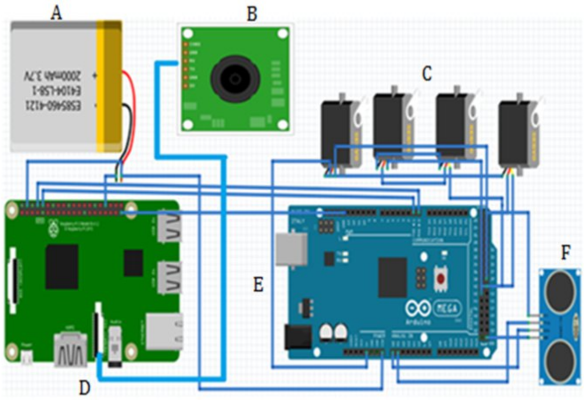


FIGURE 7. Electrical Design

2.4 DENAVIT-HARTENBERG FOR KINEMATICS ANALYSIS ARM ROBOT MANIPULATOR

Robot motion analysis is simulated by SciLab's RSTX toolbox. Denavit-Hartenberg (DH) parameters are required for the simulation derived from arm robot shown in figure 6b, and the parameters are given in Table 2

TABLE 2.
DH Parameter of Arm Robot Manipulator in Figure 6b

Joint	θ	d	a	α
1	$\theta 1$	90	0	-1,57
2	$\theta 2$	0	100	0
3	$\theta 3$	90	0	-1,57
4	$\theta 4$	128	13.5	0

3. RESULT AND DISCUSSION

3.1. PID CONTROLLER DESIGN

PID controller is required to get the robot's smooth motion. In this study, the PID controller design is simulated in SciLab. The gains (Kp, Kd, and Ki) are decided intuitively to get the best response. Figure 8, 9, 10, 11, 12, and 13 show the PID controller design.

By adjusting the gains (Kp, Kd, and Ki), the best response is achieved, indicated by short transient time, small overshoot and stable steady state. Figure 9a, 10a, 11a, 12a, and 13a show the intuitive design of Kp, Kd and Ki to get the response shown in 9b, 10b, 11b, 12b, and 13b.

The first design is in figure 9a and the result is in figure 9b where the result is long transient time and overshoots are visible before the steady state. In the first design, Ki and Kd are set to be 0; therefore, in this design, the applied controller is called P-controller, where only Kp gain is considered.

Figure 10 and 11 are designed to show the importance of Kp gain. Design in figure 10a and 11a show where Kp is set to be 0. In figure 10a, Ki is set to be 40, and in figure 11a, Kd is set to be 40. The results shown in figure 10b and 11b are unstable responses.

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Figure 12 shows PID controller design where KP is 50, Ki is 2 and Kd is 3. The design in figure 12a gives a stable result with short transient time; however, the overshoot is still occurs shown in figure 12b. Finally, the PID controller design in figure 13a gives the best response in figure 13b where the transient time is short, no visible overshoot, and stable steady state.

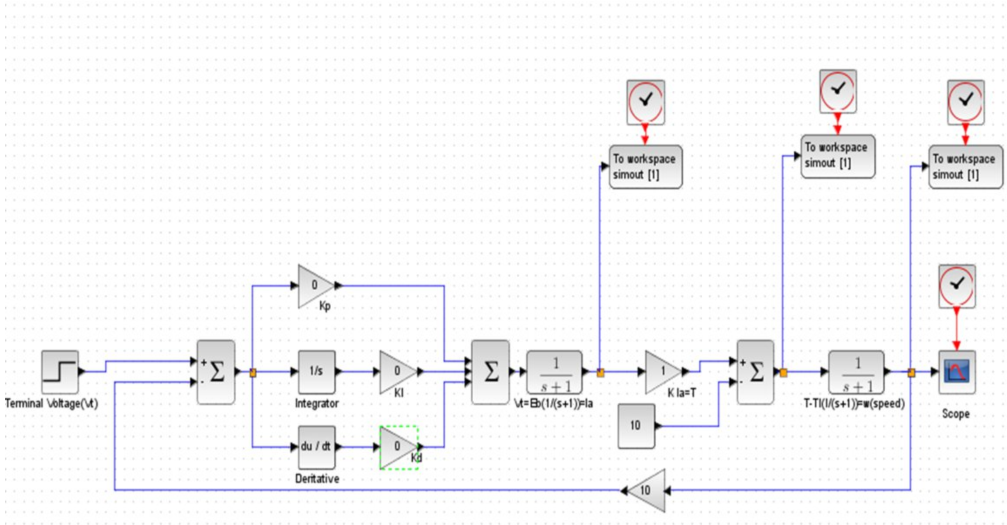


FIGURE 8. PID controller design setup

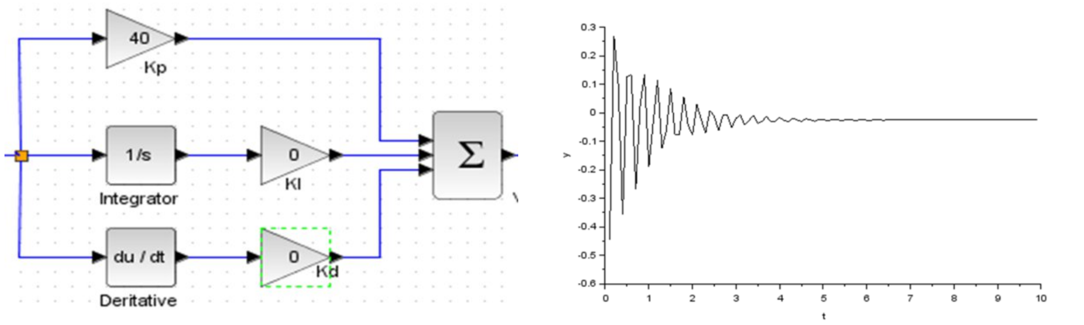


FIGURE 9. PID controller design where Kp is 40, Ki is 0, and Kd is 0

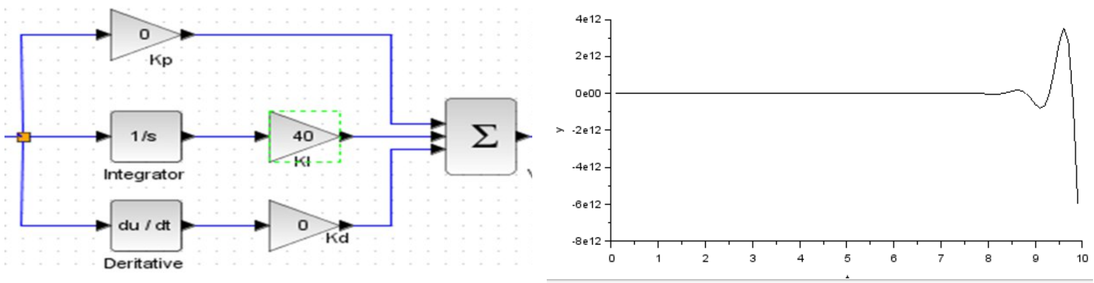


FIGURE 10. PID controller design where Kp is 0, Ki is 40, and Kd is 0

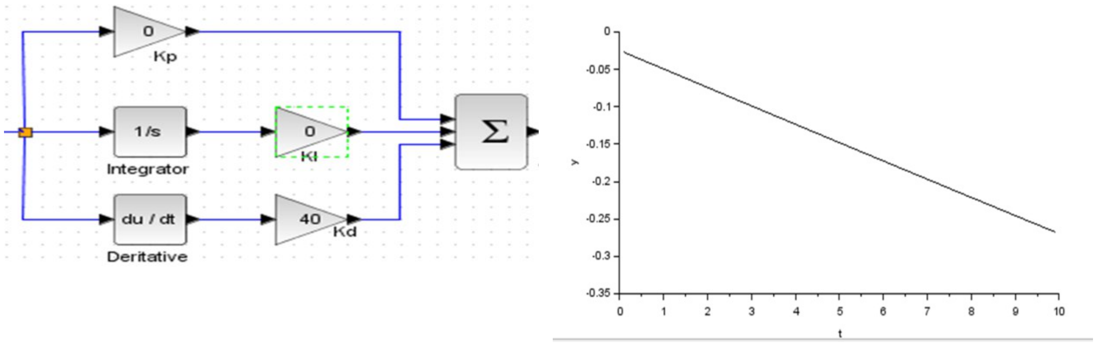


FIGURE 11. PID controller design where Kp is 0, Ki is 0, and Kd is 40

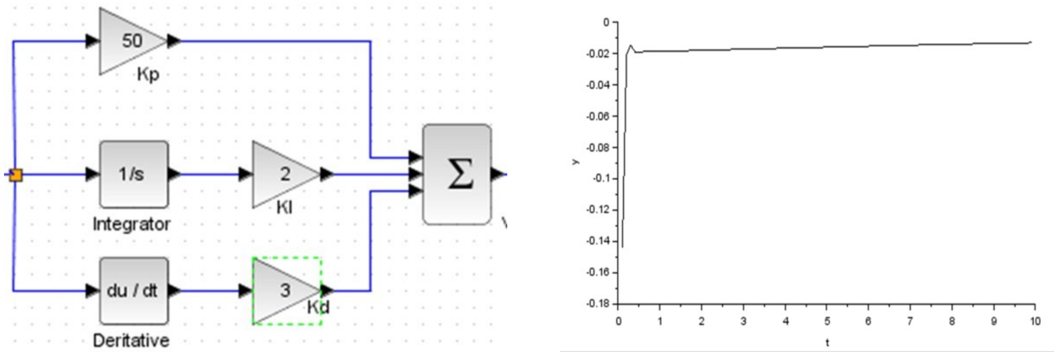
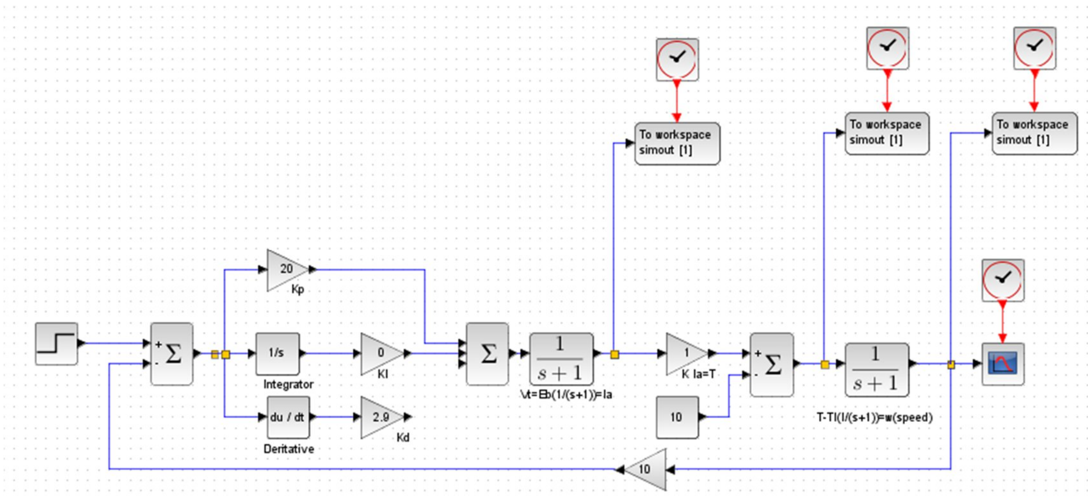


FIGURE 12. PID controller design where Kp is 50, Ki is 2, and Kd is 3



(a) Gains setup

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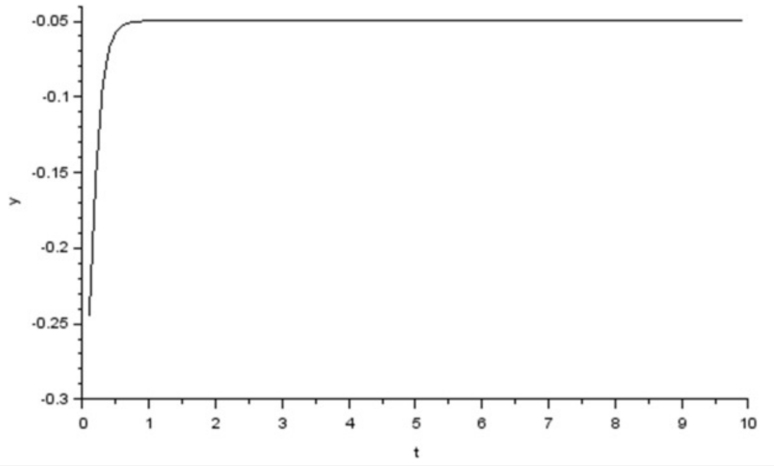


(b) Controller's response

FIGURE 13. PID controller design where Kp is 20, Ki is 0, and Kd is 2

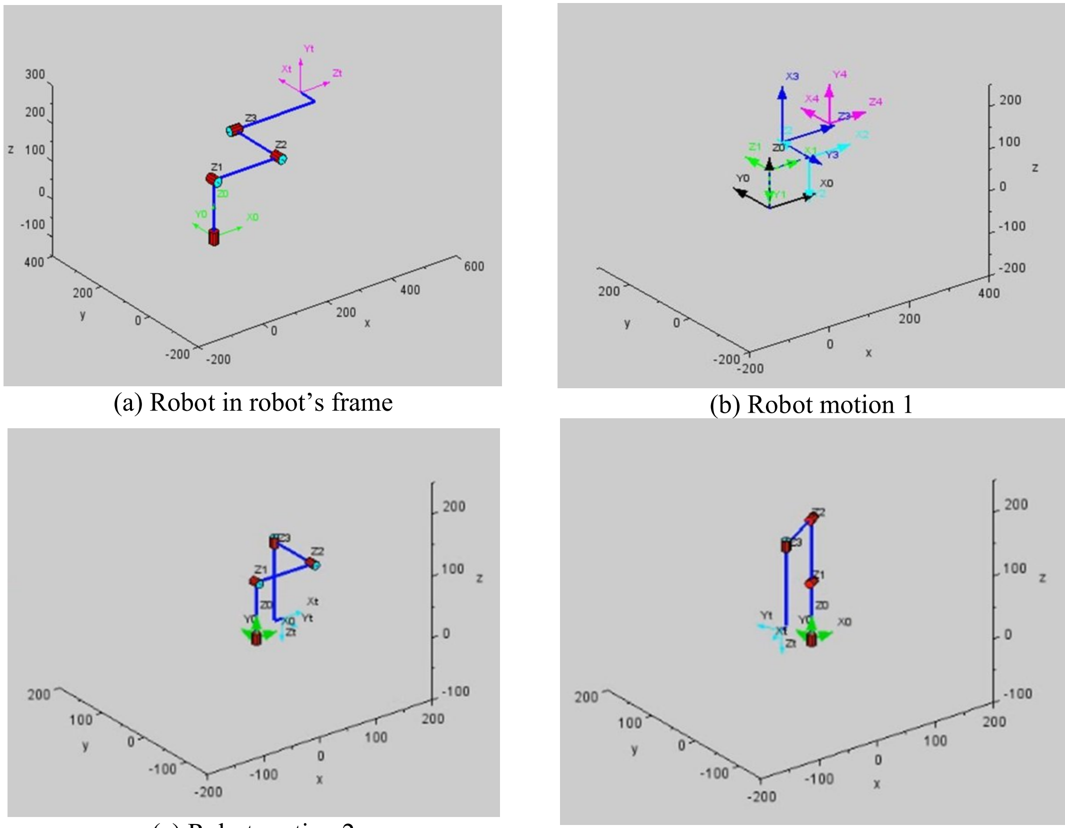
3.2. ROBOT MOTION IN ITS WORKSPACE

The simulation of 4 DOF Arm Robot Manipulator is conducted in RTSX toolbox SciLab to show robot motion in its workspace. The simulation parameters are given DH analysis in table 1, and based on the table, the syntax of the simulation are

```
L(1) = Link([0 90 0 -pi/2]);
L(2) = Link([0 0 100 0]);
L(3) = Link([0 90 0 -pi/2]);
L(4) = Link([0 128 13.5 0]);
fourlink=SerialLink(L,'ARMSv.01','4-link robot');
Robotinfo(fourlink)
PlotRobot(fourlink,[0 0 -pi/2 -pi/2]);
PlotRobotFrame(fourlink,[0 0 -pi/2 -pi/2],'hold');
t = [0:0.1:1]';
arm = [2*%pi/3*t -1*%pi/2*t %pi/2*t -1*%pi/2*t]
AnimateRobot(fourlink,arm);
```

where L(1)-L(4) shows the four links of the arm robot manipulator, the parameters achieved by DH analysis through inverse kinematics. "Robotinfo" shows the robot's information. "PlotRobot" is to plot robot motion in robot's workspace. "PlotRobotFrame" is to plot robot's graphic in robot's frame.

Figure 14 shows robot motion simulation. Robot parameters are achieved by listing the Denavit-Hartenberg parameters and inputted them in RSTX toolbox. The simulation shows how the robot moves inside its workspace.



(a) Robot in robot's frame

(b) Robot motion 1

(c) Robot motion 2

(d) Robot motion 3

FIGURE 14. Simulation of robot motion

4. CONCLUSION

This paper presents Fuzzy-PID controller of a 4 DOF arm robot manipulator applied in industry. The design started with FLC design to detect the manipulated object. FLC decides robot motion based on color green detection. The mechanical and electronics designs are also presented. Robot motion is simulated by RSTX toolbox in SciLab to checked whether the robot moves as expected. The simulation of robot motion is possible by inputting the DH parameters derived from mechanical design. PID controller is combined with FLC to ensure the motion smoothness and stability

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